DESIGN OF REDUCED ORDER MODEL FOR A LARGE-SCALE SYSTEM

SHORT SYNOPSIS

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by

Ms. Pragati Shrivastava Deb
Registration number: 18/PhD/108

Under the supervision of
Dr.Leena.G
Professor, EEE Department

FACULTY OF ENGINEERING AND TECHNOLOGY

MANAV RACHNA INTERNATIONAL INSTITUTE OF RESEARCH & STUDIES

SECTOR-43, SURAJKUND –DELHI ROAD, FARIDABAD – 121001

FACULTY OF EEE

Certificate

I hereby declare that the short synopsis "DESIGN OF REDUCED ORDER MODEL OF LARGE-SCALE SYSTEM" being submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy in Electrical & Electronics Engineering under faculty of Engineering Technology of Manav Rachna International Institute of Research & Studies, Faridabad during the academic year 2018-2019.

It is a bona fide record of original work carried out under the supervision of Dr.Leena.G Professor, Faculty of EEE and has not been submitted in full or part to any other university or institute for degree or diploma. Further, it is certified that short synopsis is plagiarism free and proof has been submitted.

Signature of the Supervisor
Dr.Leena.G
Professor, Faculty of EEE

(Pragati Shrivastava Deb)
Registration number: 18/PhD/108

(Chairman, DRC)

Chairperson, CDP

ABSTRACT

In the past decades, Model order reduction (MOR) has demonstrated its robustness and wide applicability for simulating large scale mathematical models in engineering and sciences. Such reduced order models (ROM) are useful not only for analysis and simulation of the system but also for the design of reduced complexity controllers. Wide application of MOR has been also found in optimization and control. Several reduction methods are available for reducing the order of large-scale linear SISO & MIMO systems in time domain & frequency domain. Some mixed methods have been developed by combining the algorithm of two different reduction methods. But MOR methods for nonlinear systems are not well researched. It has been found that many problems confront with complex nonlinear MOR methods like computational complexity, error bound etc. By seeing the importance to improve the performance & accuracy of nonlinear MOR systems, the aim of the research would be to develop the strong dimension reduction method for nonlinear system which approximates the original one effectively and some important properties of the original system are also preserved.

Key words: Reduced order model (ROM), Single input single output (SISO), Multiple input multiple output (MIMO), Model order reduction (MOR).

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1.INTRODUCTION

Systems with higher orders or higher processing rates needs to be controlled for Engineering problems. The dynamics of these physical systems are represented by higher order simultaneous linear differential equations. It has been found that the order of the matrix A of the state space model of such systems is very large. It will not be possible to work with the original form of a complex systems and also the analysis, synthesis and design of such higher order systems are difficult, expensive and time consuming on economic and computational attentions. Therefore, in such cases, it is required to study the process of approximation to get a simpler model. Several methods exist which estimates the 'dominant' part of the system in higher order and helps to find a reduced system with similar characteristics same as the original system.

1.1Approaches of Model Order Reduction

Generally, model order reduction is done in two ways:

A. Time Domain: In this approach, first system dynamics are converted into first order linear differential equation (means state space form), consider an nth order linear time invariant system which is represented by Eqns. (a) & (b) as:

$$x(t)= Ax(t) + Br(t)\ldots. \text{ (a)}$$

$$y(t)= Cx(t) + Dr(t)\ldots. \text{ (b)}$$

Where, x(t) - state vector (n dimension)

r(t) - input vector (dimension m)

y(t) - output vector (dimension q)

$A_{n\,X\,n}$, $B_{n\,X\,m}$, $C_{q\,X\,n}$ and $D_{q\,X\,m}$ are matrices.

B. Frequency Domain: In this approach, first it is required to obtain Laplace transform of differential equation and then the transfer function of the system with all the initial conditions set to zero has to find out.

Let the higher order system, transfer function is expressed as:

$$G(s) = \frac{b_1 s^{n-1} + \ldots\ldots\ldots\ldots + b_n}{a_0 s^n + \ldots\ldots\ldots\ldots + a_n}$$

Let us assume that a reduced order model R(s) of order 'r'< which approximate the system G(s) is given by

$$G(s) = \frac{b_1 s^{r-1} + \ldots\ldots\ldots\ldots + b_r}{a_0 s^r + \ldots\ldots\ldots\ldots + a_r}$$

1.2 Model order reduction Methods:

Different techniques were developed for reducing the higher order LTI systems into reduced model. Methods applied for model order reduction in time domain are balanced truncation, singular perturbation, aggregation, Krylov subspace, Hankel norm methods. In frequency domain Pade approximation, Routh approximation, Routh stability, stability equation, pole clustering methods are used for reduction. Denominator and numerator polynomial of transfer function model have been approximated by using these different approaches. Mostly these reduction methods are based on the preservation of dominant poles of higher order original systems in reduced model. Because dominant poles of dynamical systems are used to control their performance and non-dominant poles are used to ensure that the transfer function of controller can be realized by physical components.

Several mixed reduction techniques based on retention of dominant poles have been presented in frequency domain and in time domain. When each of these methods applied on a particular system, has shown both advantages and disadvantages. In spite of several methods available, none of the methods always gives the best results in terms of stability, error analysis and structure preservation.

Moreover, this work is limited as order reduction techniques for some specific systems like multiple input and multiple output and second order systems are not included. Currently the focus is given on MOR methods which can be applied on linear systems having multiple input and multiple output.

2. LITERATURE REVIEW

Literature Review based on Linear model order reduction methods

Various techniques were presented for order reduction to examine higher order LTI systems in the time domain and also in frequency domain.

Balanced truncation Method:

In time domain, balanced truncation is the most accepted and effective method for the model order reduction.

To reduce the computational complexity & provide reliable reduced model, (Taylor and Al-saggaf, 2010) derived approximate balanced-truncation reduced order models for large scale systems. In extension of linear time invariant system , (Abbas and Werner, 2011) proposed method of balance truncation and frequency weighted linear parameter-varying (LPV) model reduction, using structural balancing for discrete time linear system.Instead of using ordinary gramians, (Taylor, Tahavori and Shaker, 2013) uses interval gramians in the reduction process in order to progress the correctness of the approximation within the applied time

interval. The merit of this method lies in the preservation of stability, high efficiency and accuracy, making it suitable for the model reduction with practical relative error.

Based on partial-fraction-expansion idea, (Sreerama, Sahlanb, Mudac, Fernandoa and Iua, 2013) presented some new results on a frequency weighted balanced truncation technique.

Further without linearizing the original system (Besselink, Wouw, Scherpen, Nijmeijer, 2014) extended the balanced truncation technique of linear system to the nonlinear systems by introducing incremental balanced truncation method. Because of incremental observability and incremental controllability, this method well preserves the stability property.

The survey paper Baur, Benner and Feng, (2014) has been reviewed based on few of the admired MOR methods with theoretic background for linear as well as non-linear large-scale dynamical systems. For dealing with linear problems, Balanced truncation (BT) is the best-chosen method as it preserves the stability & provides a bounded global computable error. The standard Balanced Truncation does not preserve the passivity of the system. Therefore, for preserving passivity, many balancing related model reduction techniques were implemented. One of the methods is Square root of balanced truncation, computes a balance & stable reduced system & satisfies BT error bound. But this method is not advisable to compute for highly unbalanced systems which gives reduced order model of ill conditioned transformation matrices. Hence Balancing free MOR methods for highly unbalanced systems were developed. Another class of method mentioned is cross Gramian, which comprises the information about the observability and controllability of the system. In all the above-mentioned methods, the first step is to compute the system Gramians which involves the solutions of two Lyapunov equations of the similar dimension as the original system. Thus, it increases computational complexity and storage requirement of Balanced Truncation and similar related methods. To overcome this problem, many iterative methods like Krylov, tensor Krylov Subspace, factorized sign function iteration, multi grid methods, smith iteration, method based on optimization have been developed. Now a days because of advances in techniques, large scale Lyapunov equations and progress in computer hardware, improves the implementation of BT & of balancing related model order reduction methods like singular perturbation approximation, frequency weighted BT and balanced stochastic truncation.

Further for MJL systems ,(Farhood and Beck, 2014) discussed the method of balanced truncation with coprime factors reduction . Coprime factor reduction spread the application of

the BT technique to the class of mean square detectable and stabilizable MJL systems.

Zhu, Zhang, Sreeram, Shammakh & Ahmad., (2015), investigate the problem for MJL time delay systems along with input sector-bounded nonlinearities.

Wittmuess, Tarin, Keck, Arnold and Sawodny, (2016) introduced a new method in the extension of the balanced truncation method to create low-order models from large systems with parameter dependent. In this method, in contrary to interpolation-based approach for the result of the parametric model order reduction problem, with reduced computation power this method allowed calculation of the reduced system along with the corresponding projection matrix for different parameter values.

Qi, Wang, Liu, and Dimitrovski, (2016) applied balancing of empirical controllability and observability covariances to determined the reduce order model of nonlinear power systems that are considered about the operating region. Unlike existing MOR methods, in this method, there is no need to linearized the higher order system but is directly applied on nonlinear system.

Pade approximation Method:

Another well-known methodology of model order reduction for linear systems is created on Krylov subspaces also referred as pade approximation or moment matching method. These methods efficiently work on circuit simulation, simulation of machine tools & many engineering applications. In this method, model order reduction is based on deriving the MOR in such a way that the initial few time moments of the reduced model match with the original model. In frequency domain among all methods, Padé approximation is the eminent technique for the MOR of LTI models.

For obtaining stable reduced order model, (Chen, Chang and Han, 2007) presented a computationally simple combined method consisting of stability-equation and the continued-fraction for reducing high order SISO systems and multivariable systems .

Shamash, (2007) introduces the method of model order reduction of LTI system that combines the aspects of the modal methods of reduction and the time-moments.

Lepschy and Viaro, (2007) try to solve the problem of unstable model & too small stability margin of classic Pade technique.

Taylor and Wan, (2007) improved the Pade approximation method by applying Mihailov stability criterion. It gives the stability guarantee of reduced order model, if the original one is stable.

Taylor and Lucas, (2007) discussed the three methods of reduction preserving the stability,

those were Schwarz approximation, modified Schwarz approximation & Stability equation method. It has been shown that these methods were closely related to multipoint Pade approximation methods.

In the survey paper,(Baur, Benner and Feng, 2014) discussed the issues related to moment matching methods. Initially Asymptotic Waveform evaluation (AWE) method has been developed which is numerically not stable because the moments in this method are explicitly computed. To overcome this problem numerically more strong methods were introduced such as Pade Via Lanczos & PRIMA. To match the transfer function over a wide frequency range, Arnoldi & rational Lanczos methods were used. In general, it was observed from the literature that the pade approximation method doesn't give the guarantee of producing reduced stable system even if the original system is stable.

Mixed Methods:

Further numerous approaches have been introduced by combining the structures of two different techniques.

Parmar, Mukherjee and Prasad, (2007) proposed a combined method in which zeros of reduced system is find out by using factor division algorithm and denominator by using eigen spectrum analysis. The method has been applied on real poles. The matching of the step response of reduced system with original system is quite good but, sometime reduced system become non-minimum phase. It gives the guaranty of stable reduced model if the original system is stable. In this paper author applied this method on SISO systems only. This method can be further applied on imaginary poles & MIMO systems.

Another new mixed method presented by (Vishwakarma, C. B. and Prasad, R. 2009) In this scheme, modified pole clustering algorithm is developed & numerator elements are determine using Genetic Algorithm. This method is applied only on stable system & may be tried on unstable systems.

Further Taylor, Vishwakarma and Prasad, (2014) proposed a mixed method in the combination of clustering technique to reduce the denominator and numerator by Pade approximation . It takes time for computation and in some cases become non-minimum phase lower order system. Further this method can be applied for multivariable linear system. (Vishwakarma, 2011) suggested a combined technique for model order reduction of the large-scale dynamic models. Modified pole clustering algorithm has developed to reduce the denominator and Pade approximations were used to define the coefficients of the numerator. This method is easy and

gives reduced stable models if the higher order original system is stable.

A mixed approach by combining a Eigen algorithm to obtain the denominator of reduced model and Improved version of Pade approximations for determining numerator coefficient of the higher order MIMO systems was proposed by (Singh, 2014).The author has described in detail about the eigen algorithm for real and complex conjugate poles . In this method, reduced and original order systems contain the similar most dominant eigen value. For the stable original system this method gives the reduced stable system.

Singh, Chatterjee and Vishwakarma, (2014) presented a combined technique of large scale SISO system in that numerator polynomial is found by improved Pade approximation & coefficient of denominator polynomial is obtained by Eigen algorithm. It has been found that this method is computer oriented, work efficiently & is simple to applied.

Another mixed method presented by Singh, Vishwakarma and Chatterjee, (2014) in the combination of modified cauer continued fraction to find out coefficient of numerator polynomial and modified version of pole clustering to obtain denominator coefficient. For the reduction of Kth order, this technique produces k number of reduced models.

Singh, Chatterjee and Vishwakarma, (2016) proposed another method to reduce the order of original high order SISO system. In the method, the coefficient of denominator for reduced system is attained using Eigen algorithm & the numerator coefficients are attained using factor division algorithm. Time response of reduced and original models are compared graphically. It is also concluded that this method is efficient and computer oriented. Using performance error indices parameter, this scheme is compared with existing MOR methods.

Singh, Vishwakarma and Chattterjee, (2016) proposed a method is applied on SISO, in which the improved pole clustering computes the reduced denominator of order model while Pade approximations is used to obtain the numerator. This method is computational simple, retain stability and robustness. In addition, ‘k’ is generated for reducing order models for, kth−order reduction., Forced and natural responses of ROM are closely matched with original response.

In the proposed scheme by (Narwal and Prasad, 2016) ,reduction method is applied on discrete and continuous time system. Using modified version of clustering algorithm, coefficient of denominator polynomial is obtained, whereas coefficient of numerator is obtained by applying Cuckoo Search Optimization (CSO) algorithm.

A novel interpretation technique proposed by (Sikander and Prasad, 2017) for LTI systems in which coefficient of denominator of reduced model is computed by the concept of Eigen

spectrum analysis and for obtaining numerator Cuckoo search algorithm has been developed. It has been observed that the proposed technique has the efficacy and effectiveness after comparing ISE, IAE and ITAE values of it with the different lower order systems.

Prajapati and Prasad, (2018) proposed a new MOR technique for dynamic linear systems in which the balanced truncation approach is used to obtained the denominator polynomial of ROM & numerator coefficient is calculated by factor division technique. It has been found that the existing problem of balanced truncation method of mismatching between the steady state values of higher order original & the reduced system has overcome by using this proposed method and it also preserves the stability of the reduced order model. It preserves the first rare time moments in the ROM of the higher order original system.

A composite technique of MOR has been proposed by (Sengar, Chatterjee and Singh, 2018). In this method, most dominant poles for reduced order model is being generated by MIDM and IPA technique is being used for the generation of appropriate time moments and Markov parameters to obtain the zeros of the reduced systems. This method takes less time for calculation. Also, it has been observed that step responses of approximated models are good and almost matches the pattern of original system responses. The comparisons of error index i.e. ISE and IAE of the proposed system has been done with the other error index obtained by the other well-known techniques. via MATLAB platform. ROM obtained by this method can be used to design compact controllers which can be compared with original model designed controllers.

Prajapati and Prasad, (2018) combines the dominant pole and factor division method to compute the denominator polynomial and numerator polynomial of reduced order system respectively. This approach gives sufficient degree of approximation. In the reduced system this scheme preserves the initial few time moments, stability and steady state value of the original model. This method has least performance indices and very closer approximation of the reduced system with those of the original model. Therefore, the ROM obtained by this method can be applied for controller design and digital signal processes. A new Routh approximation technique in simplified form is presented by (Prajapati and Prasad, 2018).Basically Routh approximation involves both the alpha and beta parameters as seen in the literature, but in this new technique alpha parameters are involved to make the projected scheme more simpler. Routh approximation technique is applied to find the coefficient of the denominator polynomial and a simple algorithm is applied to find the numerator polynomial.

From comparison of step response of both the reduced and original systems, it has been found

Table 1 Summary of Model order reduction methods used in mixed combination

Sr. No.	Investigator	Proposed method	Applied on	Type of System	Pros	Cons
1	(Parmar, Mukherjee and Prasad, 2007)	Eigen spectrum analysis & Factor division algorithm	10th order-only real poles 4th order- only real poles 8th order - only real poles 6th order -only real poles	SISO SISO SISO MIMO	Extended for system with imaginary poles	sometimes develop Tendency to become Non minimum phase
2	by (Vishwakarma, C. B. and Prasad, R. 2009)	Modified pole clustering algorithm & Genetic Algorithm	6th order--only real poles	MIMO	May be extended to unstable system	not appliedon SISO system
3	(Taylor, Vishwakarma and Prasad, 2014)	Clustering technique & Pade approximation	4th order -only real poles 4th order- only complex conjugate poles	SISO	Extented to MIMO	somtimesDevelop Tendency to become Non minimum phase
4	(Vishwakarma, 2011)	Modified pole clustering algorithm & Pade approximations	8th order - only Real poles 7th order- complex conjugate poles	SISO	Equally applicable on MIMO system	
5	(Singh, 2014)	Eigen algorithm & Improved pade approximations	6th & 4th - only real poles	MIMO	Reduceses the Proble of Non minimum phase	Not applicable for SISO
6	(Singh, Vishwakarma and Chatterjee, 2014)	Modified pole clustering & modified cauer continued fraction	4th order- only real poles 6th order - Real poles	SISO MIMO		
7	(Singh, Chatterjee and Vishwakarma, 2014)	Eigen Permutation algorithm & Improved pade approximation	6th order--only real poles 4th order - complex conjugate poles 8th order -only real poles	SISO SISO		
8	(Singh, Chatterjee and Vishwakarma, 2016)	Eigen algorithm & factor division algorithm	6th & 8th -only real poles 4th order - only complex conjugate poles	SISO SISO		not valid for MIMO
9	(Singh, Vishwakarma and Chattterjee, 2016)	Improved modified pole clustering & improved Pade approximations	8th order - real poles 4th order - complex conjugate poles 8th order-real & complex conjugate poles 10th order - real poles	SISO SISO SISO SISO	Extented to MIMO , LTI DST systems	somtimesDevelop Tendency to become Non minimum phase
10	(Narwal and Prasad, 2016)	Modified clustering algorithm & Cuckoo Search Optimization (CSO) algorithm	4th order -complex conjugate poles 4th order - real poles 6th order- Only real poles 4th & 8th order - complex conjugate poles	SISO SISO MIMO discrete time		
11	(Sikander and Prasad, 2017)	Eigen spectrum analysis & Cuckoo search algorithm	4th order -complex conjugate poles 8th order - real & complex conjugate poles 7th order- real & complex conjugate poles order - Real poles	SISO SISO SISO MIMO		
12	(Prajapati and Prasad, 2018)	Balanced truncation & factor division	4th order - complex conjugate 3rd order- complex conjugate 5th order - complex conjugate 16th order-complex conjugate	SISO SISO SISO SISO	Extented to MIMO	Tendency to become Non minimum phase
13	(Sengar, Chatterjee and Singh, 2018)	Modified Inverse Distance Measure(MIDM) & Improved Pade Approximation (IPA)	8th order- Real poles 8th order - real & complex conjugate poles 4th order - only complex poles	SISO SISO SISO	Extented to MIMO	
14	(Prajapati and Prasad, 2018)	Dominant pole approach & factor division method	3rd & 8th order - real & complex conjugate poles 6th order - only Real poles	SISO MIMO	Further applied on the large-scale discrete and interval systems	
15	(Prajapati and Prasad, 2018).	Routh approximation technique & simple algorithm	4th order - complex conjugate 5th order - complex conjugate 6th order - Real poles	SISO SISO MIMO		
16	by (Singh, Kumar and Samuel, 2019)	Improved pole clustering & factor division algorithm	4th order -complex conjugate 8th order - real poles 6th order - Real poles 10th order- complex conjugate 4th order - complex conjugate	SISO SISO MIMO MIMO discrete- time	LTI time delay and interval systems	

that both are having approximately similar characteristics. A computationally simple and computer oriented reduction method is applied on higher order LTI continuous-time, SISO, MIMO & discrete-time systems proposed by (Singh, Kumar and Samuel, 2019).For determining denominator polynomial of ROM , improved pole clustering method has been used and to compute the coefficients of the numerator polynomial, factor division algorithm is applied. To show the versatility of the projected scheme it is also applied on 4^{th} order linear discrete- time system.

3. GAPS IN RESEARCH STUDY

With the literature review, it can be concluded that, in case of linear systems, theoretically Reduced order models are well understood in respect of error analysis, stability, and structure preservation as well as efficient to compute. Each of the methods discussed in literature has merits and demerits when tried on a particular system. In spite of several schemes available, none of the approach gives best results in terms of stability, error analysis and structure preservation.

As per Table 1, it has been observed that all the methods (latest) as used are related to SISO, MIMO, discrete system till 10^{th} order and only one technique has been used to reduce the 16^{th} order which is implemented on SISO system highlighting the limitations beyond.Not much work has been done on MOR for Multivariable systems. Work is also limited to discrete time systems and no method has been developed for LTI time delay and interval large scale systems.

4. OBJECTIVES OF THE STUDY

To develop appropriate mixed combination of order reduction techniques to reduce the order of linear large-scale system more than 10^{th} order.

To design a reduced order model to minimize the simulation time and complexity of the system. The stability and passivity of the large-scale dynamic system will be maintained with this reduced order model.

To propose a combination of two mixed reduction methods on a particular higher order system and comparison in terms of error indices and the step response will be done.

To design a controller with the reduced order model and it would be applied to the large-scale systems.

5. METHODOLOGY TO BE ADOPTED

Try to develop a combination of mixed method which would be applicable on higher order systems above tenth order SISO, MIMO, discrete systems considering all types of nature of poles.

To develop fast numerical method to reduce computational complexity ie. requiring less simulation time to reduce higher order system.

Comparison of the proposed method with the other well-known methods available in literature would be done in respect of error indices and will be try to get the best results in terms of accuracy and stability.

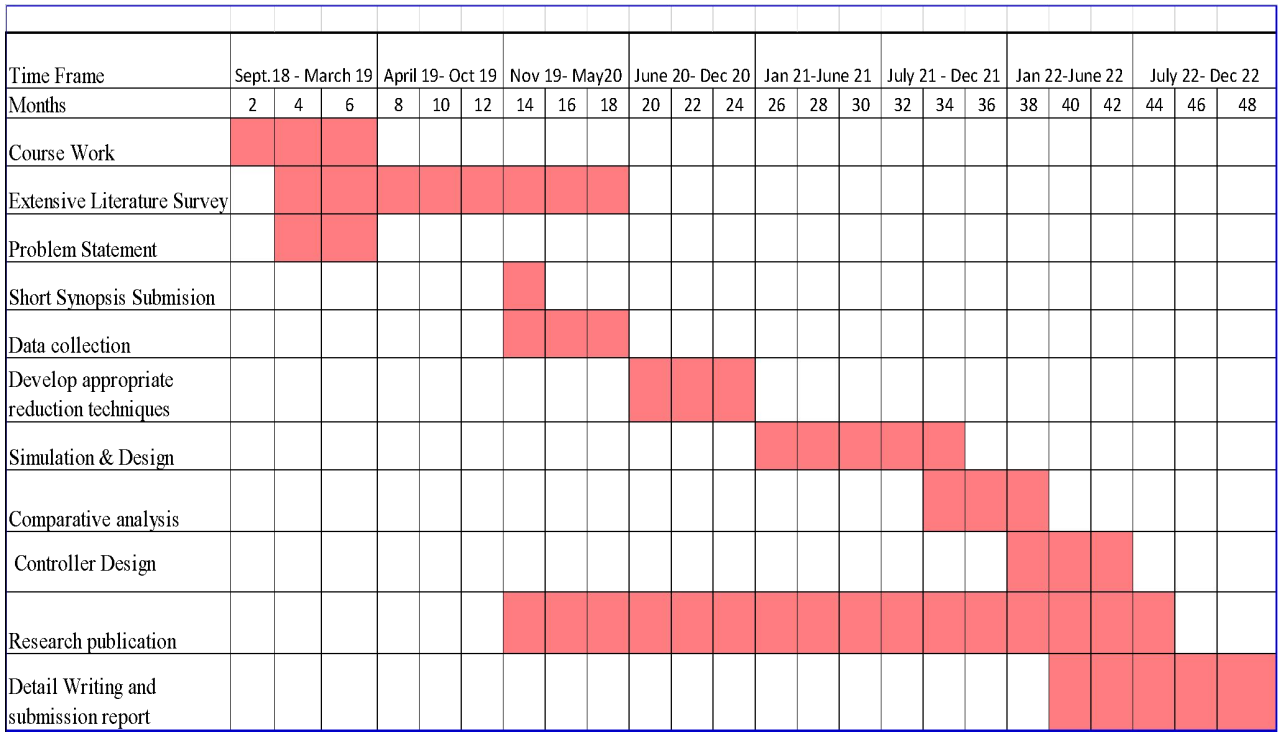
Then a controller would be designed for reduced model which can directly control the original system.

Simulation of the adopted MOR technique will be done using MATLAB/ SIMULINK software.

6. EXPECTED OUTCOME OF THE RESEARCH

1. Reduce the computational complexity, simulation time and preserve the stability and passivity of the large-scale dynamic system by designing appropriate model order reduction technique.
2. Improve the transient and steady state response of original system.

7. PROPOSED TIME FRAME


Time Frame
Sept.18 - March 19
April 19- Oct 19
Nov 19- May20
June 20- Dec 20
Jan 21-June 21
July 21 - Dec 21
Jan 22-June 22
July 22- Dec 22
Months
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48
Course Work
Extensive Literature Survey
Problem Statement
Short Synopsis Submision
Data collection
Develop appropriate reduction techniques
Simulation & Design
Comparative analysis
Controller Design
Research publication
Detail Writing and submission report

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DESIGN OF REDUCED ORDER MODEL FOR A LARGE-SCALE SYSTEM

SHORT SYNOPSIS

by

Ms. Pragati Shrivastava Deb
Registration number: 18/PhD/108

Under the supervision of
Dr.Leena.G

1. INTRODUCTION

Systems with higher orders or higher processing rates needs to be controlled for Engineering problems. The dynamics of these physical systems are represented by higher order simultaneous linear differential equations. It has been found that the order of the matrix A of the state space model of such systems is very large. It will not be possible to work with the original form of a complex systems and also the analysis, synthesis and design of such higher order systems are difficult, expensive and time consuming on economic and computational attentions. Therefore, in such cases, it is required to study the process of approximation to get a simpler model. Several methods exist which estimates the 'dominant' part of the system in higher order and helps to find a reduced system with similar characteristics same as the original system.

1.1Approaches of Model Order Reduction

Generally, model order reduction is done in two ways:

A. Time Domain: In this approach, first system dynamics are converted into first order linear differential equation (means state space form), consider an nth order linear time invariant system which is represented by Eqns. (a) & (b) as:

$$x(t)= Ax(t) + Br(t)\ldots. (a)$$

$$y(t)= Cx(t) + Dr(t)\ldots. (b)$$

Where, x(t) - state vector (n dimension)

r(t) - input vector (dimension m)

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